

# R-Mode receiver development for medium frequency signals

Lars Grundhöfer, Stefan Gewies  
Institute of Communications and Navigation

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Knowledge for Tomorrow



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# Introduction

## Maritime navigation

- ▶ Goal: collision avoidance
- ▶ Need for resilient PNT
- ▶ Depend on GNSS
- ▶ Shutdown Loran-C



# Introduction

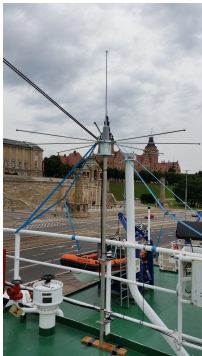
## R-Mode

- ▶ Terrestrial navigation system
- ▶ Signal-of-opportunity
  - ▶ Maritime Radio Beacon
  - ▶ Automatic Identification System (AIS)





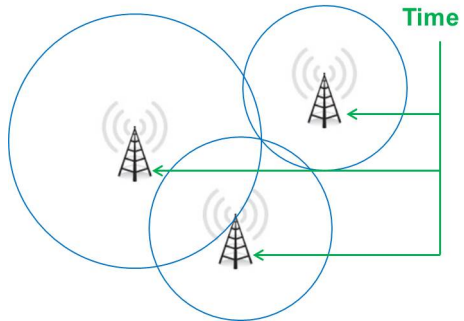
# Introduction



# Introduction

## Pseudo range estimation

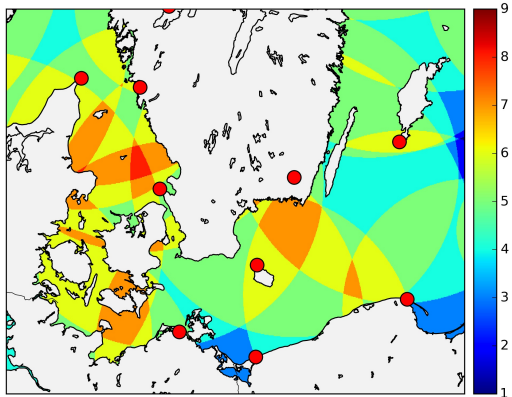
- ▶ Bit timing
- ▶ Phase



# Why Maritime Radio Beacon?

- ▶ Range around 300km
- ▶ Propagation as ground wave
- ▶ Testbed starting 2020

<http://r-mode-baltic.eu>



# R-Mode enabled Transmitter

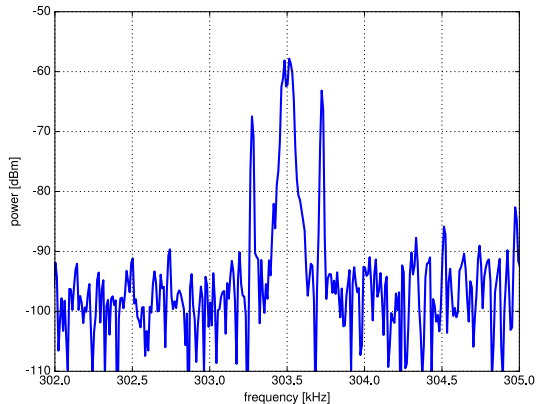
## Signal

- ▶ MSK on carrier frequency
- ▶ CW  $\pm 225$  Hz beside carrier

## Maritime Radio Beacon

- ▶ Helgoland 298.5 kHz
- ▶ Zeven 303.5 kHz

Power spectrum of 100000 samples (average of 1 spectra).



# Theory



# MSK Modulation

Time Signal:

$$A \sin \left( \left( \omega_c + b_k \frac{\pi}{2T_s} \right) (t - kT_s) + \varphi_k \right)$$

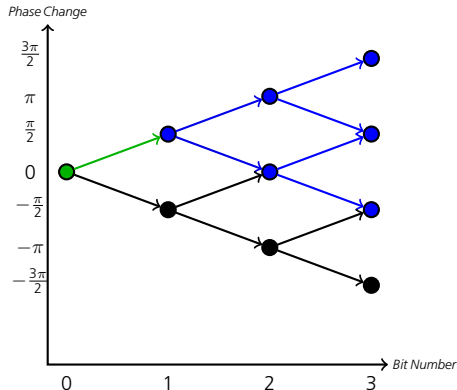
$\varphi_k$ : Memory of MSK

$\omega_c$ : Carrier frequency

$b_k$ : k Bit

$k$ : Number of sent bits

$T_s$ : Bit duration



**Problem: Ambiguities of 250 m**



# Phase Estimation MSK

## Hilbert transform

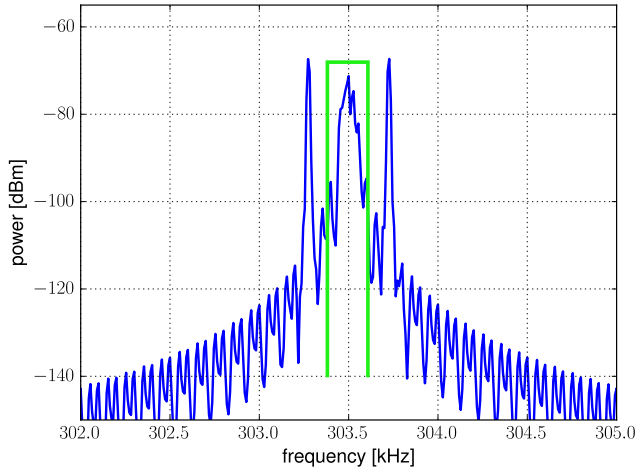
- ▶ Transform to analytic signal
- ▶ Implementation as filter
- ▶ Real time capable
- ▶ Compare to generic signal

$$\hat{X} = -jX(j\omega) \operatorname{sgn}(\omega)$$

$$g(t) = H\{f\}(t) = f(t) * \frac{1}{\pi t}$$

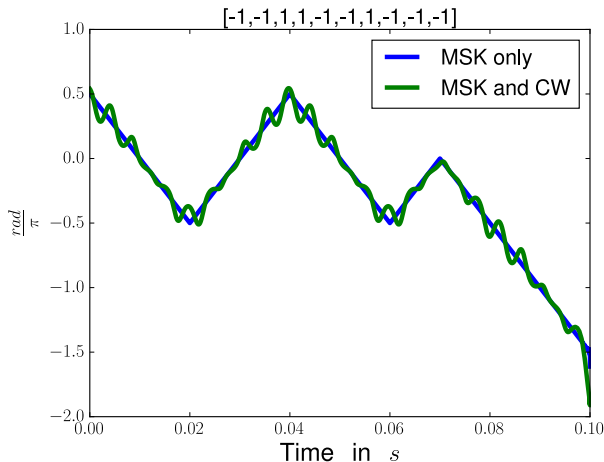


# R-Mode Signal Spectrum





# Simulation Result Hilbert Transform



- ▶ Filtered with small bandwidth
- ▶ Removed carrier phase
- ▶ Bit pattern decoded
- ▶ CW interference



# Estimate CW phase

## Likelihood Formula:

$$L = \sum_{i=1}^k \{2b_i \operatorname{Re}[e^{j\theta_i} A(\omega_i)] - b_i^2\}$$

with

$$A(\omega) = \frac{1}{N} \sum_{n=0}^{N-1} (X_n - jY_n) e^{-jn\omega T}$$

$X$ : Input vector

$Y$ : Hilbert transform of  $X$

$b$ : Amplitude vector

$k$ : Number of tones

$N$ : Number of samples

$\frac{1}{T}$ : Sample rate

$\omega$ : angular frequency

$\theta$ : Phase offset



# Estimate CW phase

Maximum Likelihood Estimation :

$$\tilde{b}_i = |A(\omega_i)|$$

$$\tilde{\theta}_i = \arg[A(\omega_i)]$$

for

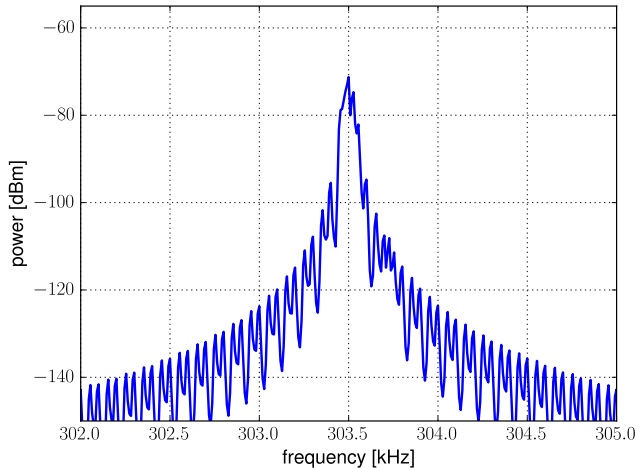
$$\arg \max_{\omega_j} (L)$$

**Ambiguities CW: 1km**

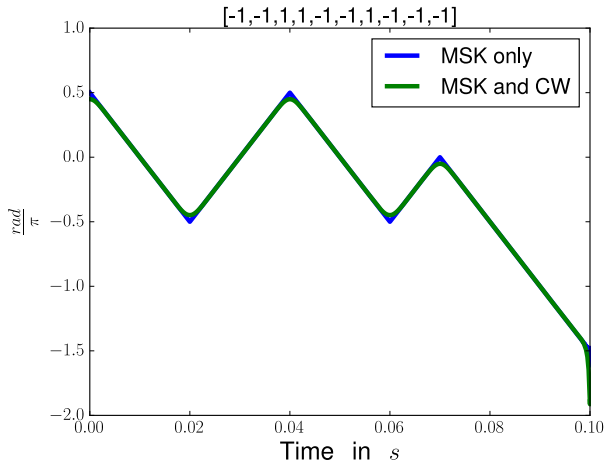
**Ambiguities Beat: 600km**



# R-Mode Signal Spectrum with CW estimation



# Estimate CW phase



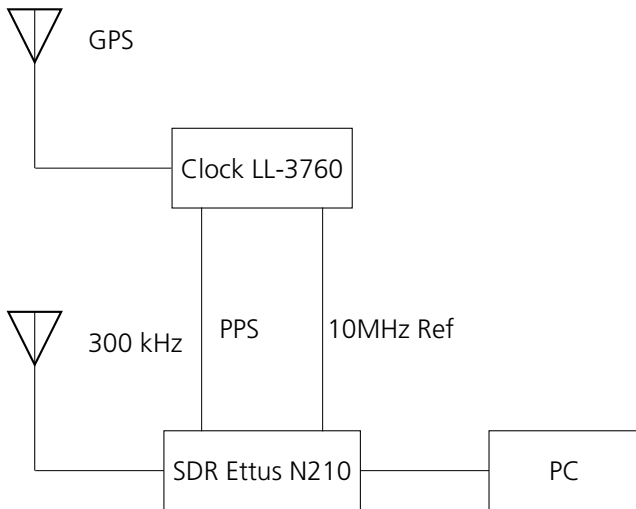
- Filtered
- Removed carrier phase
- Estimate CW
- Remove CW



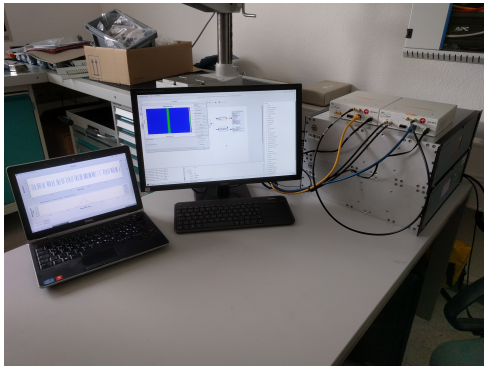
# Measurements



# Measurement Setup Overview



# SDR



- ▶ Decoding RTCM
- ▶ GNU Radio
- ▶ Synchronisation
- ▶ Encoding RTCM

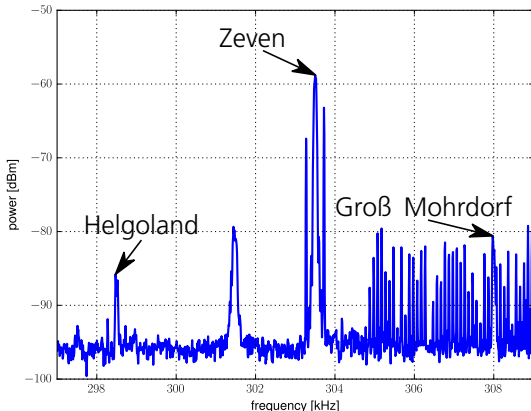




# Measurement Campaign



# External Electromagnetic Interference

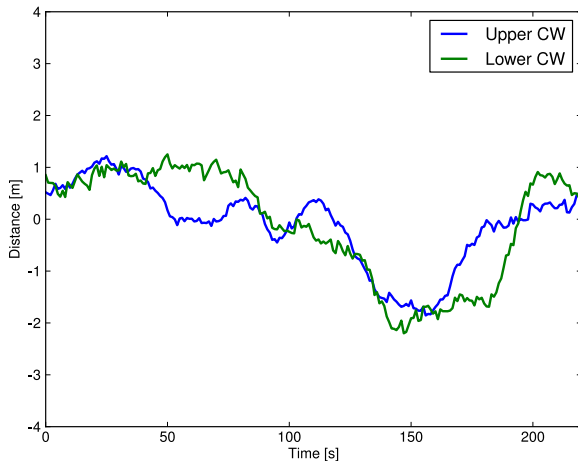


External EMI causes

- ▶ Non directional beacon
- ▶ Solar cells
- ▶ Faulty devices



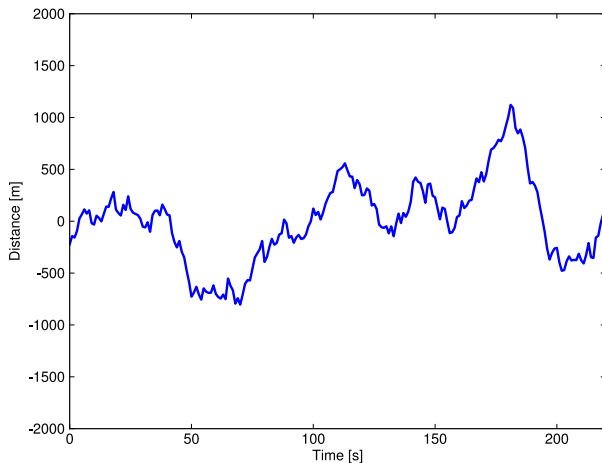
# Distance Estimation CW



- ▶ 1Ms sample rate
- ▶ 1Hz steps
- ▶ vary 3.6m
- ▶ Standard deviation: 1.76m



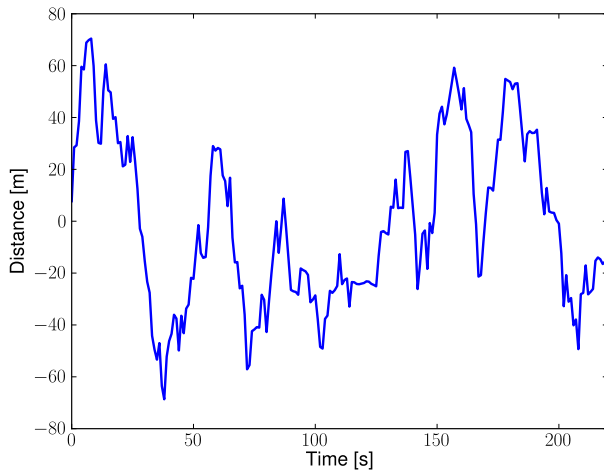
# Distance Estimation CW-Beat



- ▶ 1Ms sample rate
- ▶ 1Hz steps
- ▶ vary 2km
- ▶ Standard deviation: 1km



# Distance Estimation MSK



- ▶ 1Ms sample rate
- ▶ 1Hz steps
- ▶ vary 140m
- ▶ Standard deviation 100m



# Conclusion



# Conclusion

- ▶ Phase estimation
- ▶ SDR Maritime Radio Beacon receiver
- ▶ EMI on SDR receiver in MF



# Outlook

- ▶ Find reason for disturbances
- ▶ Further investigation of phase estimation
- ▶ Correction factor







# Estimate MSK phase

## Maximum likelihood estimation

$$\Lambda(x|\tilde{\alpha}, \tilde{\theta}, \tilde{\tau}) = \exp \left\{ -\frac{1}{2\sigma_n^2} \sum_{k=0}^{NL_0-1} \left| x(k) - \sqrt{\frac{2E_s}{T}} e^{j[\tilde{\theta} + \psi(\tilde{\alpha}, kT_s - \tilde{\theta})]} \right|^2 \right\}$$

**No Solution for small SNR**

$x(t)$ : received signal

$\tilde{\alpha}$ : test values data bit

$\tilde{\theta}$ : test value phase

$\tilde{\tau}$ : test value bit timing

$\psi(\alpha, t)$ : Phase information

$E_s$ : power per bit



# Estimate CW phase

## Maximum likelihood estimation

$$f(Z, \alpha) = \left( \frac{1}{\sigma^2 2\pi} \right) \exp \left[ -\frac{1}{2\sigma^2} \sum_{n=0}^{N-1} (X_n - \mu_n)^2 + (Y_n - \nu_n)^2 \right]$$

with

$$\alpha = [\omega, b, \theta]$$

$$\mu_n = b \cos(\omega t_n + \theta)$$

$$\nu_n = b \sin(\omega t_n + \theta)$$



# Estimate CW phase

## Maximum likelihood estimation

$$L = \sum_{i=1}^k \{2b_i \operatorname{RE}[e^{j\theta_i} A(\omega_i)] - b_i^2\} - \frac{1}{N} \sum_{m \neq i} \sum_m b_i b_m \sum_n \cos(n\omega_i T - n\omega_m T + \theta_i - \theta_m)$$

$$A(\omega) = \frac{1}{N} \sum_{n=0}^{N-1} (X_n - jY_n) e^{-jn\omega T}$$

